IMAGE TEST TARGET FOR VISUAL DETERMINATION OF DIGITAL IMAGE RESOLUTION

DESCRIPTION

BACKGROUND OF THE INVENTION

Field of the Invention

The present invention generally relates to digital imaging and, more particularly, to optical evaluation and resolution measurement of digital imaging cameras, especially digital cameras useful for applications such as machine vision, character or feature recognition, bar code reading and automated inspection systems.

Description of the Prior Art

The capture of images on various light sensitive media has been known and widely practiced for over one hundred fifty years. During the last fifty years, optical sensors have been developed to generate electrical signals directly from the illumination pattern incident on the sensor. Even more recently, there has been considerable interest in developing signals which can be directly operated upon by digital data processing equipment for various applications such as optical inspection in manufacturing processes and automatic control systems. Automatic control systems such as vehicle guidance often rely on detection, identification and tracking of visual targets which must be accomplished with extremely high reliability, particularly when concerns for public safety, operation of costly apparatus and the like are presented. Such reliability is often

limited by optical performance of image capture apparatus.

Visual targets may be of any form which can be extracted from the remainder of an image within the required response time with the data processing capacity which is practical to provide. The image from which the target must be extracted may vary widely in content and lighting conditions. That is, the natural features (or "background clutter") of the image may not be easily controllable and the appearance of those features in an image may vary widely with lighting conditions while the features of a visual target must be extracted therefrom at high speed with limited processing. For that reason, visual targets which have features presenting particularly high contrast of relatively simple geometric form such as concentric circles are much preferred at the present state of the art. When such features are used, the critical parameter of optical system performance for target detection, identification and tracking is image resolution.

Unfortunately, optical resolution is often particularly difficult and expensive to quantitatively evaluate, particularly when derived from sensors having discrete areas corresponding to individual pixels, such as are provided by charge coupled devices which are currently preferred for image capture in most applications. In such devices, the individual pixel areas may be extremely small but each pixel area is, of course, finite and the response to radiation (e.g. light) imaged upon each pixel area is effectively averaged over that individual area. Thus, the sensor, itself, imposes a limit on resolution and complicates measurement of resolution of the optical image capture system as a whole.

At the same time, available image resolution is critical to the design of the visual targets to be employed. That is, the contrasting features of a target must be of sufficient size to be unambiguously discriminated at distances appropriate to other constraints of the application and within the resolution of the image capture system such as reasonable distance over which control is to be exercised in a vehicle guidance system, the potential variation in distance of an object having features or characters to be read or the transverse dimensions of contrasting features to be detected and processed at a distance which may or may not be well-regulated. Therefore, accurate and readily available knowledge of resolution of an image capture system is essential to efficient design of reliable systems for each of an extremely wide variety of applications. Further, it is useful and important to be able to rapidly test individual image capture devices or cameras when the device is placed in service to ascertain that it can perform as intended.

SUMMARY OF THE INVENTION

It is therefore an object of the present invention to provide a technique by which resolution of an optical system can be readily determined by inspection of a single image formed therewith.

It is another object of the invention to provide an imaging target which can be easily fabricated at very low cost.

It is a further object of the invention to provide a method of determining at least resolution and alignment of an imaging system with apparatus limited to a target pattern.

In order to accomplish these and other objects of the invention, a method of measuring resolution of an imaging system is provided comprising steps of imaging a target including a plurality of sub-fields having a progression of image feature size and pitch encompassing the resolution of the imaging system to produce a captured image, inspecting the captured image for presence or absence of Moire' patterns in sub-fields of the captured image, and determining resolution of the imaging system from feature size and pitch in sub-fields.

In accordance with another aspect of the invention, a target for determining resolution of an imaging system is provided including a plurality of sub-fields, each subfield including a plurality of features, the plurality of subfields having a progression of image feature size and pitch encompassing the resolution of said imaging system, referred to an object plane of the imaging system.

BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing and other objects, aspects and advantages will be better understood from the following detailed description of a preferred embodiment of the invention with reference to the drawings, in which:

Figure 1 is a top or side perspective view of a simplified optical system including a sensor and a test target in accordance with the invention,

Figures 2A, 2B and 2C are plan views of a test image falling on a sensor array as depicted variously in Figure 1 and including a graphical depiction of pixel outputs,

Figures 2D, 2E and 2F are plan views of best, worst and intermediate case imaging of the test image at best resolution and including a graphical depiction of pixel outputs.

Figure 3 is a portion of an exemplary test image in accordance with the invention,

Figure 4 is an image produced in accordance with the invention from which resolution of the image capture system may be determined by inspection, and

Figure 5 is an enlarged view of the region of interest in Figure 4.

DETAILED DESCRIPTION OF A PREFERRED EMBODIMENT OF THE INVENTION

Referring now to the drawings, and more particularly to Figure 1, there is shown an optical system collectively depicted as lens 10, imaging high contrast features 22, 24 of test target 20 onto a sensor comprising an array of pixel area sensors 32. A practical sensor array 30 might include a matrix of several hundred to several thousand sensors on a side (e.g. a 1000 by 1000 array containing one million pixels) or such an array may be simulated by a linear array, referred to as a line scan sensor, as is generally the case and depicted as any one of arrays a, b, or C. It is assumed for purposes of this discussion that the image of the test target 20 is brought to good focus on the image plane of the sensor array 30. The relative position of the test image or target 20 is not particularly important to an understanding of the invention since, at any distance of the test pattern or target 20 from the camera 40, each feature 22, 24 of test pattern 20 will subtend a particular spatial angle relative to the camera 40 and image plane 30. It is sufficient to an understanding of the invention that distances along the image plane will generally be proportional to distances such as feature width and spacing along the plane of the test target at least over a fraction of the respective areas (more or less corresponding to a sub-field as will be described below) and that levels of distortion expected from commercially available lenses are generally well below levels which could compromise successful practice of the invention.

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The maximum resolution of the image capture

apparatus/camera 40 will be determined in accordance with the invention where resolution is limited by the division of the pixel array 30 or the pitch of pixels 32. This condition will be reached when the transverse dimension of test image features ~~22, 24~~ 50, 52 equals the pitch of pixels 32 in sensor array 30. In the particular preferred test image illustrated, it will be understood that this condition will be met when each of features ~~22, 24,~~ 50, 52 which are preferably of equal width (or subtend equal angles from the center of the lens system) overlies or is the same width as a single pixel. JEO 10/24/00 JEO 10/24/00

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However, for purposes of discussion and explanation of the operation of the invention, the IMAGED features 22, 24 of the test pattern 20 are illustrated as each overlying slightly more than one pixel ~~(or row of pixels)~~ in Figure 1. Three pixel rows/columns 34 are indicated by brackets A, B and C in Figure 1 in varying positions (but equal pitch slightly differing from the target feature pitch referred to the image plane) for purposes of illustration. Consecutive pixels in a row/column 34 of sensor array 30 are shown with their corresponding pixel outputs in Figures 2A, 2B and 2C, respectively. JEO 10/24/00

It should be appreciated that each of the output signals shown for the respective pixels of the respective overlapping groups is proportional to the area illuminated (or not) by the respective features ~~22, 24~~ 50, 52 and, since the width of these features, when projected onto the image sensor array 30 is ~~less~~ GREATER than the pixel dimension, will represent a particular gray-scale value, MAX. WHITE, OR MIN. BLACK. Conversely, if the feature width is ~~greater~~ LESS than the dimensions of a pixel, zero and maximum values of the output signal will NOT be obtained with

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adjacent pixel outputs having an intermediate gray-scale value.

Accordingly, by comparing the illumination patterns from the target features projected on a sensor array, as illustrated in Figures 2A, 2B and 2C, it can be seen that target feature will be incident on varying fractions of adjacent pixels but that the location of pairs of adjacent pixels more or less equally illuminated (or not) will vary in position depending on the location of the array and the target perpendicular to the optical system axis. In other words, if the pitch of target features, referred to the image plane, differs from the pixel pitch, Moire' patterns including relatively wide features (e.g. 36) will unconditionally result from "beating" of the different spatial frequencies of the target features and pixels. JEA 10/24/00

If, on the other hand, the IMAGED target features are the same SIZE as ~~(or an integral multiple of)~~ the size of a pixel referred to the image plane Moire' patterns will not be PRODUCED ~~reduced~~ and the received image or sensor output pattern will assume one of the forms illustrated in Figures 2D, 2E or 2F. JEA 10/24/00 JEA 10/24/00 It is only when the feature width is the same as ~~or an integral multiple of~~ the pixel WIDTH ~~pitch~~ and the test image features aligned so as to be accurately projected exactly onto pixels WITHIN THE rows that no gray-scale output values will result. JEA 10/24/00 JEA 10/24/00 This best-case condition is shown in Figure 2D wherein the illuminated range 50 exactly overlays a pixel 32 of the sensor array 30 and the output is either a minimum or a maximum with no gray scale fringes.

The worst case for identical feature size is shown in Figure 2E where illuminated regions 50 are equally divided between adjacent pixels and the output is a uniform gray level. This

condition is extremely rare although theoretically equally likely as that of Figure 2D. ~~(The difference in apparent frequency of observance appears to be attributable to the ability to perceive target pattern features to very low levels of contrast or, conversely, that it is difficult to distinguish between instances of images similar to that of Figure 2D from high contrast instances of Figure 2E where the offset of the target image features and the pixels having the same pitch is small.)~~ This in no way compromises the determination of resolution since adjacent targets having even very slight differences of target feature and pixel pitches will have Moire' fringes. If the illuminated regions 50 are shifted from the condition illustrated in Figure 2F, different gray scale levels (contrast) will be output from adjacent pixels with difference increasing with shift until the condition of Figure 2D is reached with no Moire' fringes being developed at any degree of shift.

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Therefore, it is only when the features ~~22,~~ 50, 52 ~~24 are~~ projected on sensor array 30 have the same ~~or an integral multiple of the~~ pitch ~~of~~ AS the pixels 32 that the outputs of the alternating pixels will have similar values. Conversely, at other, differing relative pitches of target features and pixels, the respective pixels outputs will vary non-periodically as shown in Figures 2A - 2C and will result in aliasing in the form of a Moire' pattern having coarse vertical grey scale bands.

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(Rotational misalignment of the pixel rows of the sensor with features of the test image will cause an apparent ~~decrease~~ INCREASE in best resolution or cause the vertical bands of the Moire' pattern to be angled when the feature pitch does not match the

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pixel pitch. Therefore, the invention is also capable of testing for alignment of the image capture device 40, as well.) The pitch of the Moire' bands will decrease as the imaged feature pitch approaches pixel pitch and maximum resolution and Moire' bands will abruptly disappear altogether where the feature dimensions and pitch, as imaged, match that of the pixels 32 ~~(or a multiple thereof if the optical system rather than the sensor array limits resolution)~~. LEW 10/24/00

Contrast may be reduced depending on relative position of target features when target feature and pixel pitches are matched but the contrast of the Moire' bands will not be affected. The contrast of the pattern will also be reduced as the feature dimensions become much smaller than the pixel but this effect is not important to the invention since it is used at or near actual image resolution. Contrast will also be reduced as the resolution limits of the optical system is approached.

This effect is exploited in accordance with the present invention by imaging a plurality of sub-fields 60 providing a progression of different feature pitches and dimensions encompassing the resolution of the imaging system or camera 40, as shown in Figure 3. Human readable reference numbers 62 are preferably included which correspond to feature size and/or pitch of features in each subfield and reflect the number of features or dots per inch (or any other convenient unit) referred to the object plane. (The resolution at the image plane is fixed by sensor size and pitch. Resolution at the object plane is determined by object distance and, hence, magnification.) Additional images may be included in the target such as for indicating the direction

of progression of feature size or pitch.

The image produced by the image capture device or camera 40 is shown in Figure 4 (although the image of Figure 4 would correspond to an extension of the sub-fields of Figure 3 to finer feature dimensions and pitches). Where the feature dimensions do not exactly correspond to the resolution-limiting pixel pitch, Moire' pattern bands or fringes are evident. These appear as relatively narrow gray bands at substantial differences (e.g. at around 180 and 220) of pitch from system resolution which increase in width and separation as actual system resolution (187) is approached.

In the particular case illustrated in Figure 4 and in enlarged form in Figure 5, the actual resolution may be readily determined from inspection to be 187 lines or dots per inch. This sub-field shows no evident Moire' pattern and is framed (at 186 and 188) by sub-fields having substantial gray areas of substantially uniform tone caused by gradually changing overlap of image features with pixel rows or columns producing the Moire' pattern. It should be noted, particularly in Figure 5, that single, large Moire' fringes appear in all but the center subimage. In this manner, by choosing the subimage with the least amount of fringing, the best resolution can be readily determined by inspection even in the worst case as depicted in Figure 2E where the entire subimage is the same gray level. In other words, the Moire' pattern as produced in accordance with the invention may be considered as a beating of different spatial frequencies with the frequency of the beating diminishing with diminishing difference of spatial frequency.

In this case, also, the test pattern is well-

imaged at maximum resolution, indicating an alignment probably between the best case of Figure 2D and the intermediate case of Figure 2F. With slightly different alignment, sub-field 187 could be imaged as a substantially uniform gray while sub-fields 186 and 188 would appear substantially the same but with the broad gray scale areas in the form of low frequency Moire' fringes present.

In short, imaging such a pattern will result in an image from which actual system resolution can be determined with extremely high accuracy (e.g. within less than two lines or dots per inch or one percent or better in this case) upon quick visual inspection of the image. Thus, this effect referred to the design of a suitable visual target in regard to an image capture device or camera verifies the ability for the camera having resolution measured in accordance with the invention to produce an image from which a target having corresponding angular feature sizes can be detected, identified and tracked with minimal processing.

System

It should also be recognized that the technique in accordance with the invention is extremely inexpensive since the test patterns such as that shown in Figure 3 are the only equipment required other than the camera and imaging system itself, to which the invention is applied. These patterns can be readily generated and printed by computer and commercially available computer printers since they may be much larger than the image as projected on the sensor array 30 and resolution of six hundred dots per inch (at the larger size) is available from many laser printers of current design. High contrast of the test target may be enhanced by photographic transfer processes available at most commercial print

shops.

While the invention has been described in terms of a single preferred embodiment, those skilled in the art will recognize that the invention can be practiced with modification within the spirit and scope of the appended claims.